Delta-DOR Technology Improvements

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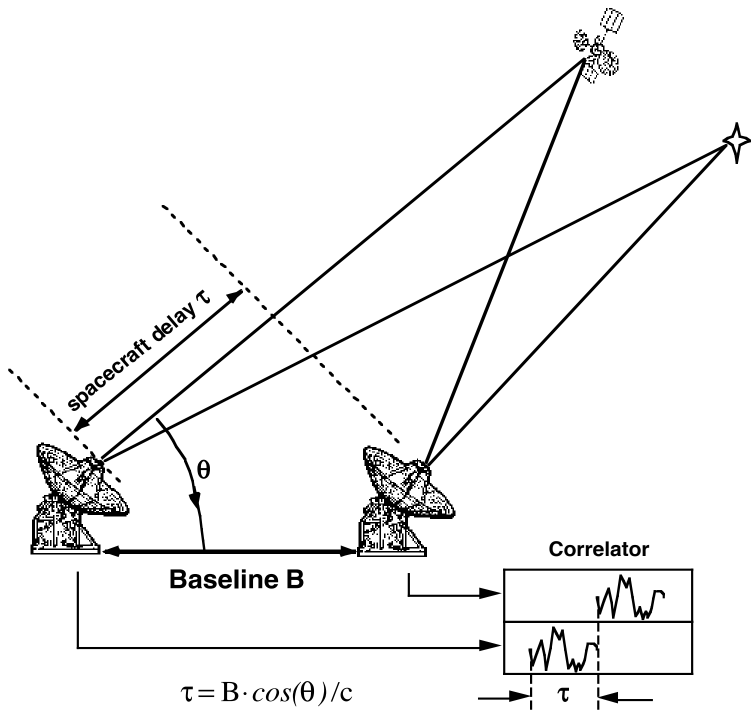
Delta Differential One-Way Ranging Overview

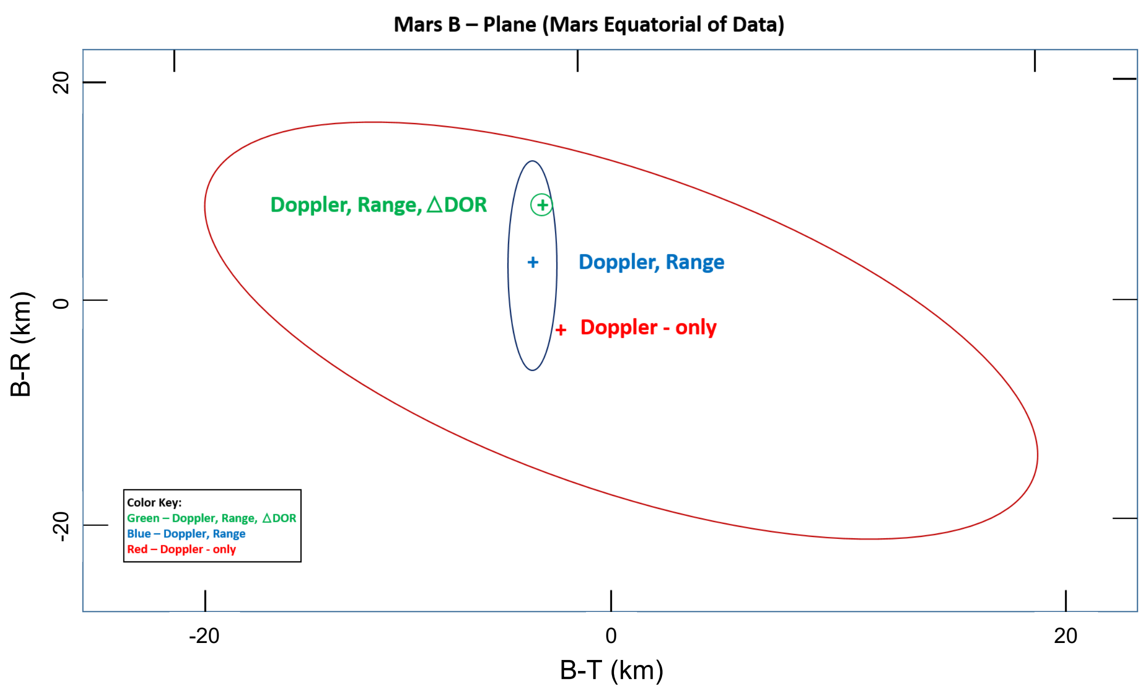
- ΔDOR uses interferometry to measure spacecraft angular position in the radio reference frame
- Observations from 2 (long) baselines are needed to measure both components of angular position



$$\tau = B \cdot cos(\theta)/c$$

Delta Differential One-Way Ranging Overview

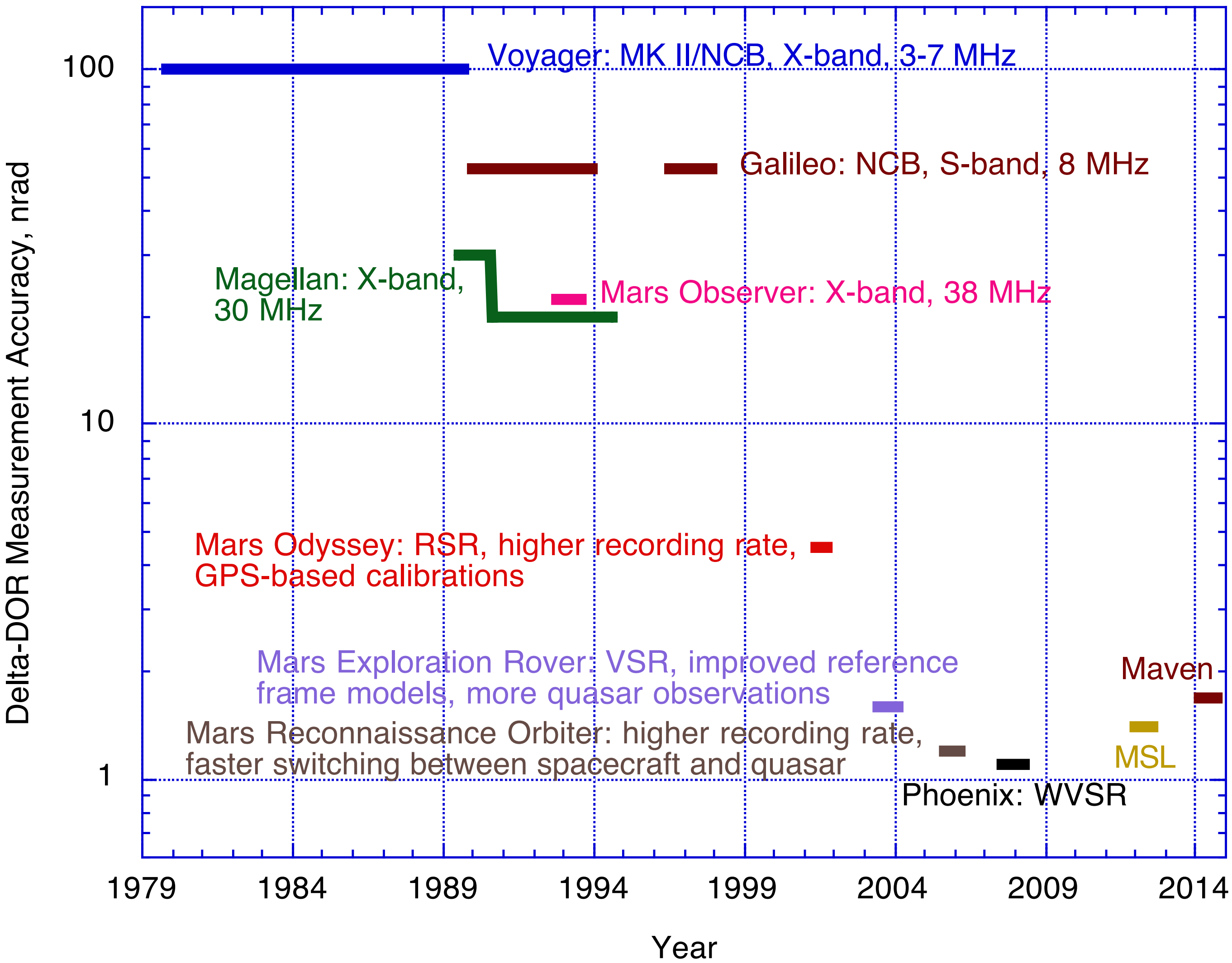
- Complements line-of-sight Doppler and range to provide plane-of-sky coordinate targeting for critical events
  - Accuracy has improved from 150 nrad (1981) to 2 nrad (present)
  - 2 nrad is 300 m plane-of-sky position accuracy at Mars (~1 AU)
  - High accuracy is needed for Mars landing



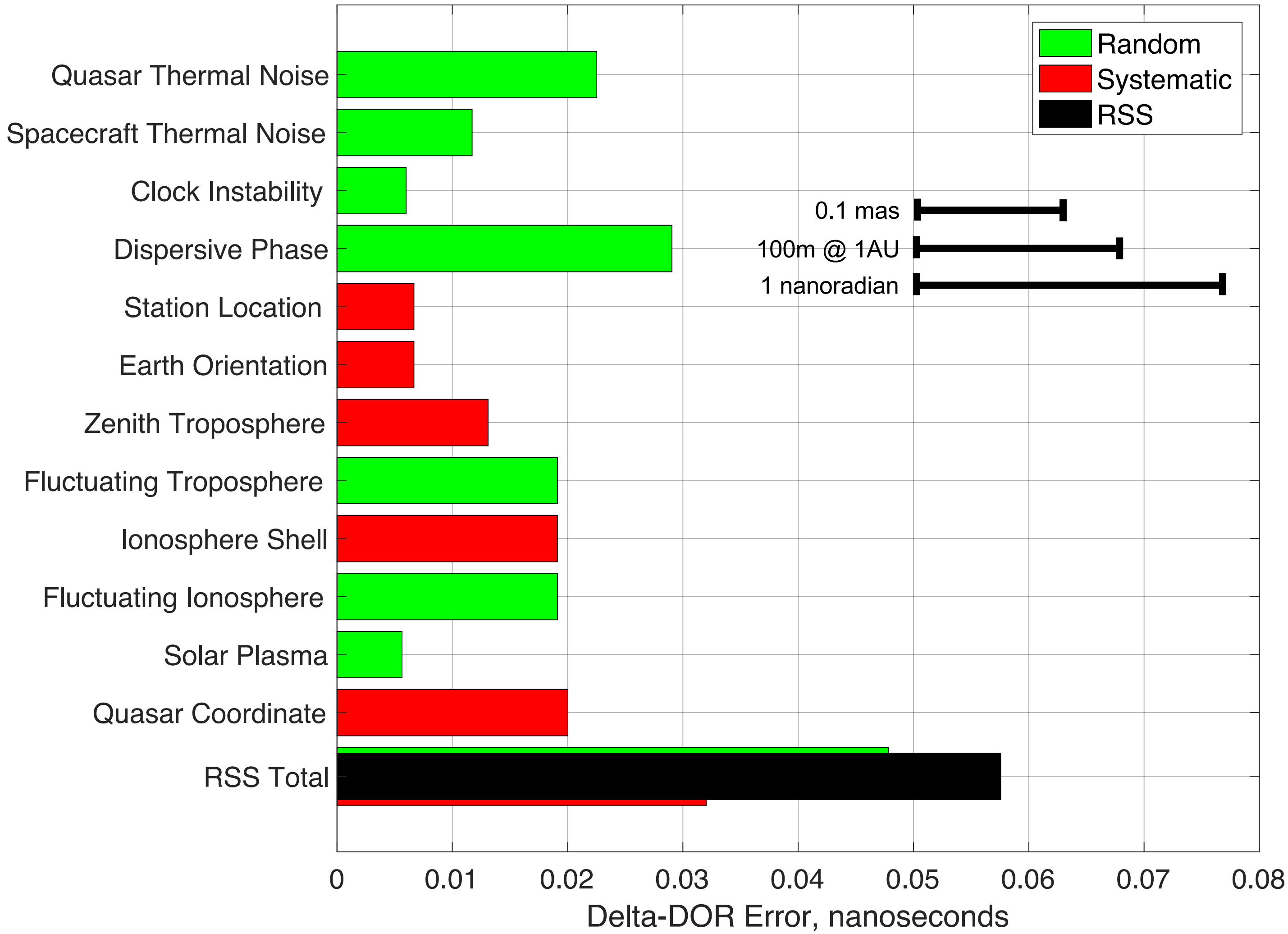
Delta-DOR Technology Development

- Delta-DOR has improved over the years by investing in technologies to reduce the limiting error sources.
- Improvements from 1981 to present-day include:
  - Spacecraft transponders with wider bandwidth DOR tones
  - Improved ground station open loop receivers
  - Higher bandwidth data recording
  - Better media calibrations
  - Better radio source catalog and reference frame
  - More sophisticated observing sequence

Delta-DOR Accuracy Improvement

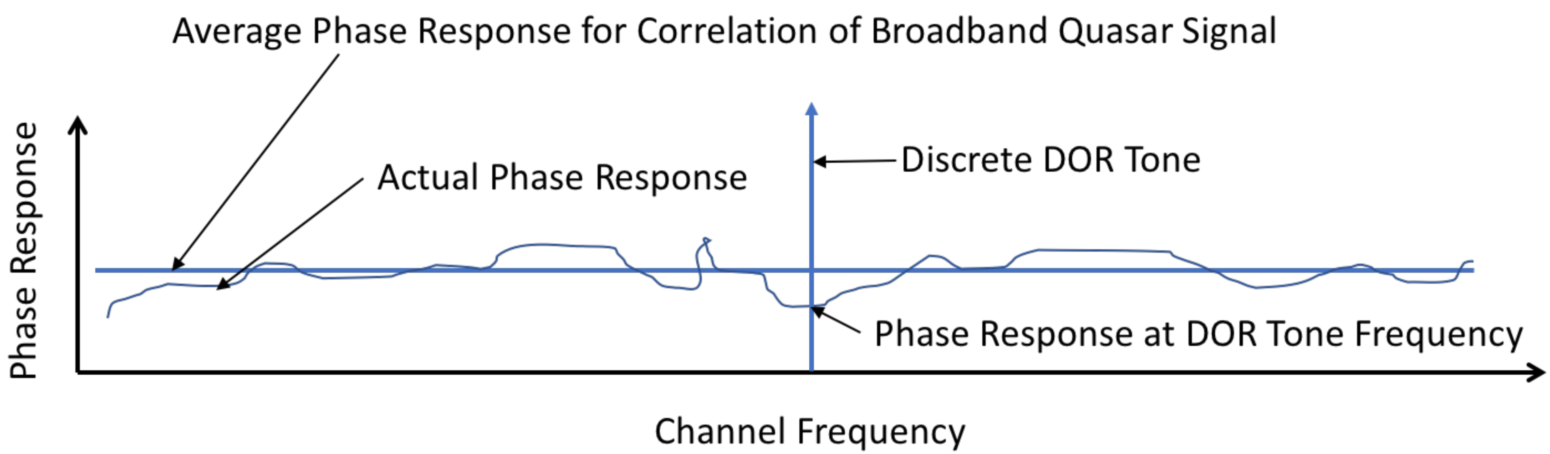


Current Delta-DOR Error Budget (X-Band)



Dispersive Phase, The Dominant Error

- Dispersive phase is the non-linear phase shift within ground station components.
  - Not common to spacecraft and quasar signals due to spectral differences in signal.
  - Remains as key error source in Delta-DOR measurements.
- Can be reduced by changing spacecraft spectrum to more closely resemble quasar spectrum

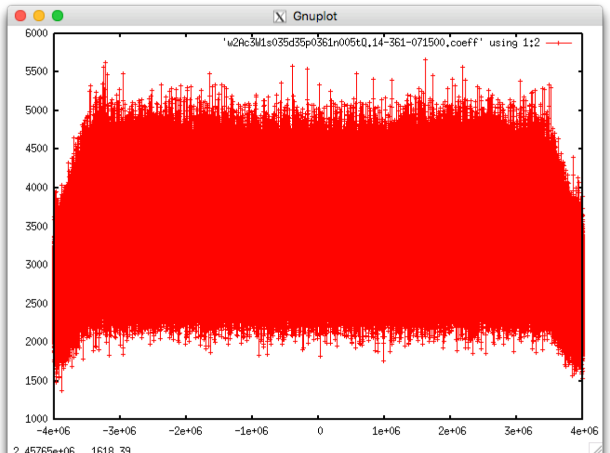


Pseudo-Noise (PN) DOR Signal

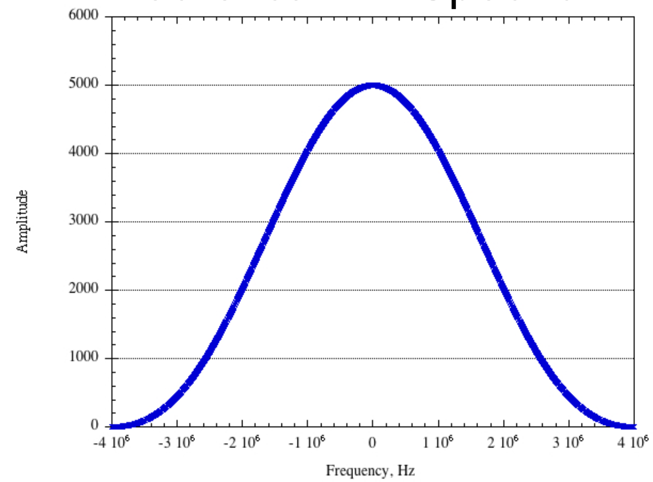
- To spread the DOR tone spectrum, the sinusoidal DOR tone can be multiplied by a PN sequence.
  - The resulting spectrum is spread by chip rate of the PN code.
    - i.e. a 8 Mcps code spreads spectrum over a 8 MHz baseband channel
  - The spectrum is further flattened by use of a square-root raised cosine filter (SRRC).
  - A long code sequence (~1ms) is used for ambiguity resolution.
- The resulting spectrum more closely resembles the quasar noise spectrum, and allows for an estimated cancellation of 90% of the phase dispersion errors.
- Use of a PN code also reduces radio interference between DOR tones and nearby spacecraft.

Pseudo-Noise (PN) DOR Signal Spectrum

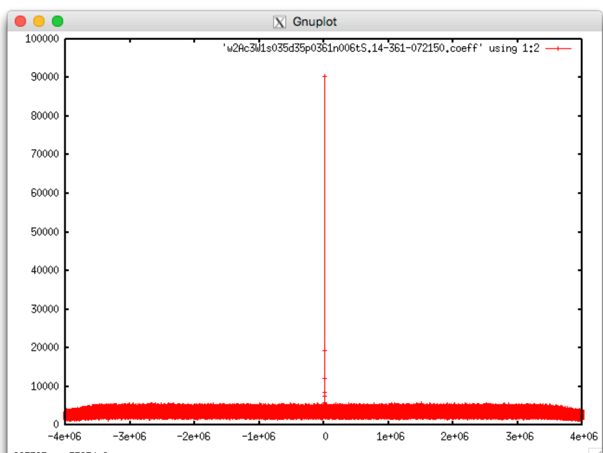
Quasar



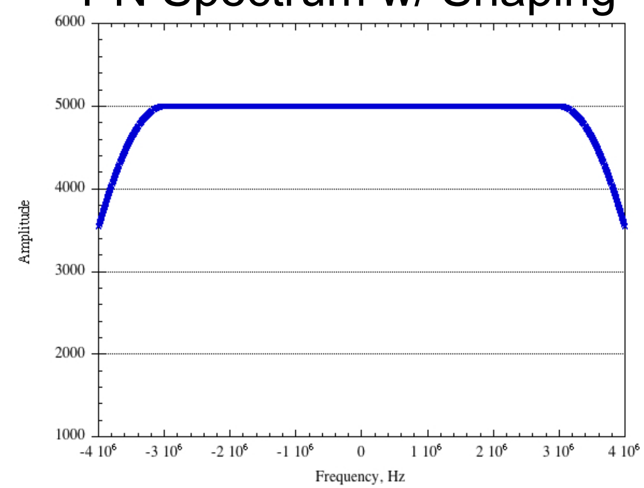
Theoretical PN Spectrum



DOR Tone



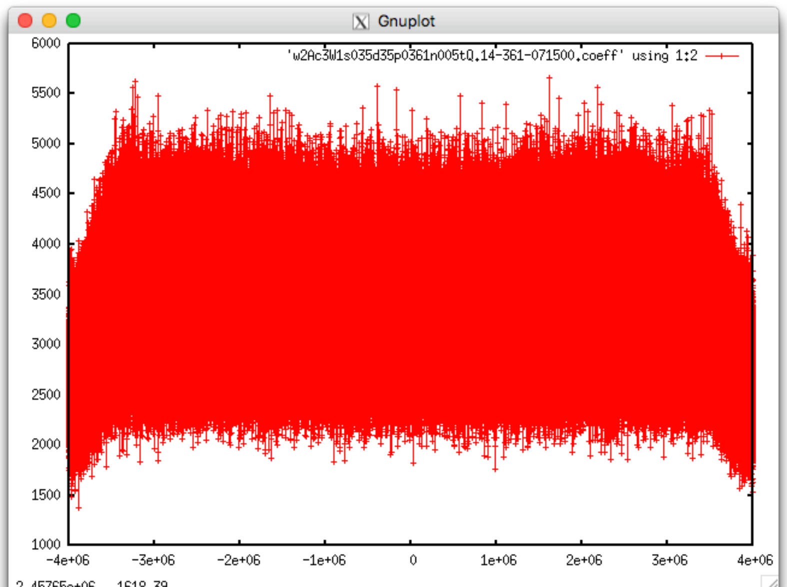
PN Spectrum w/ Shaping



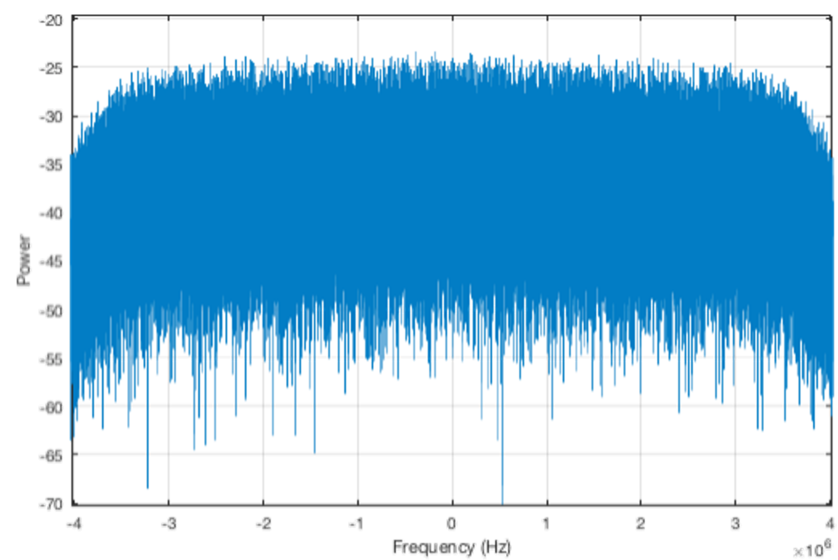
Pseudo-Noise (PN) DOR Signals

- JPL’s IRIS CubeSat radio is capable of transmitting spread spectrum PN code DOR signals.
- Recorded spectrum closely matches quasar spectrum.

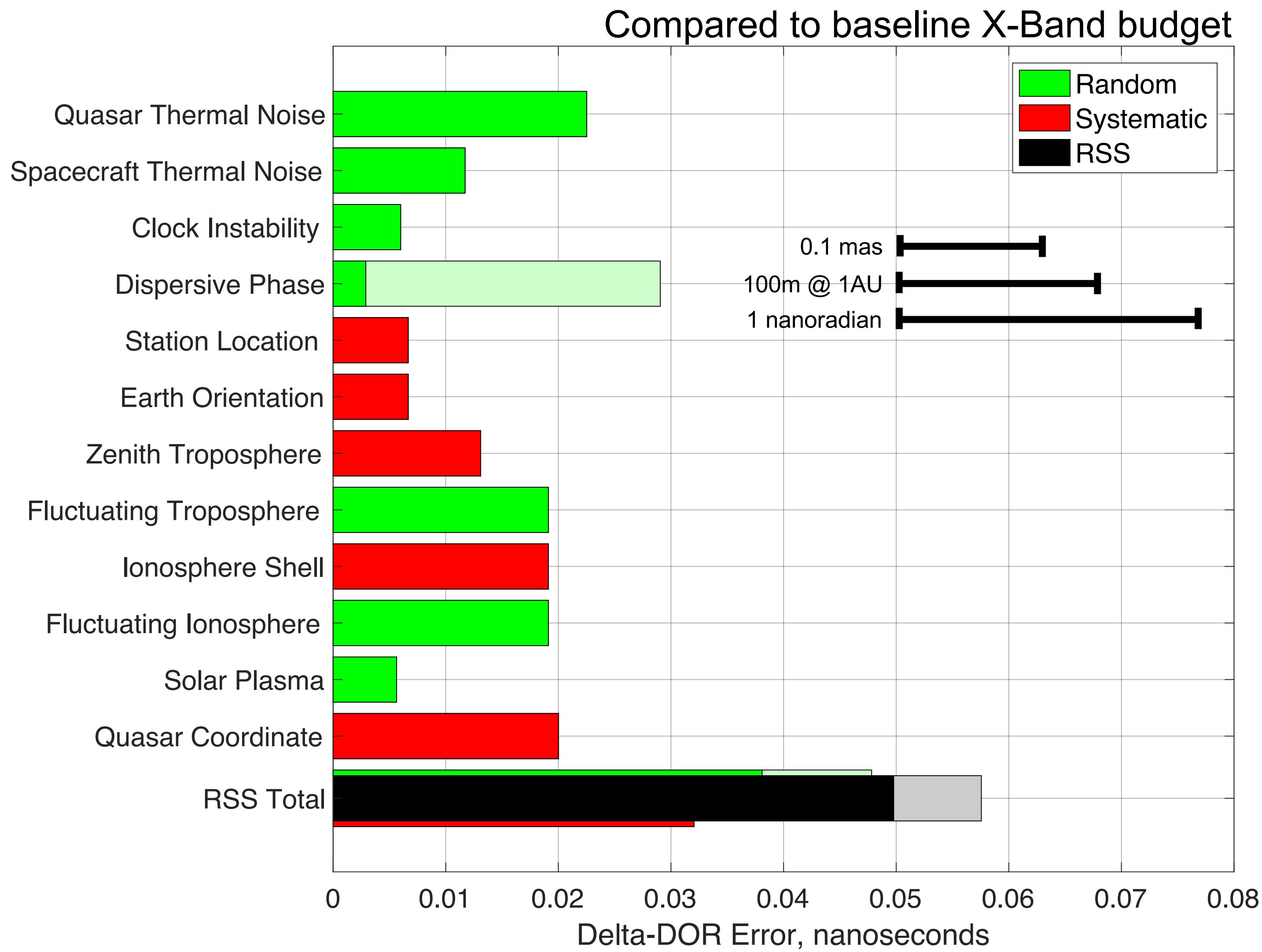
Quasar



JPL Transmitter



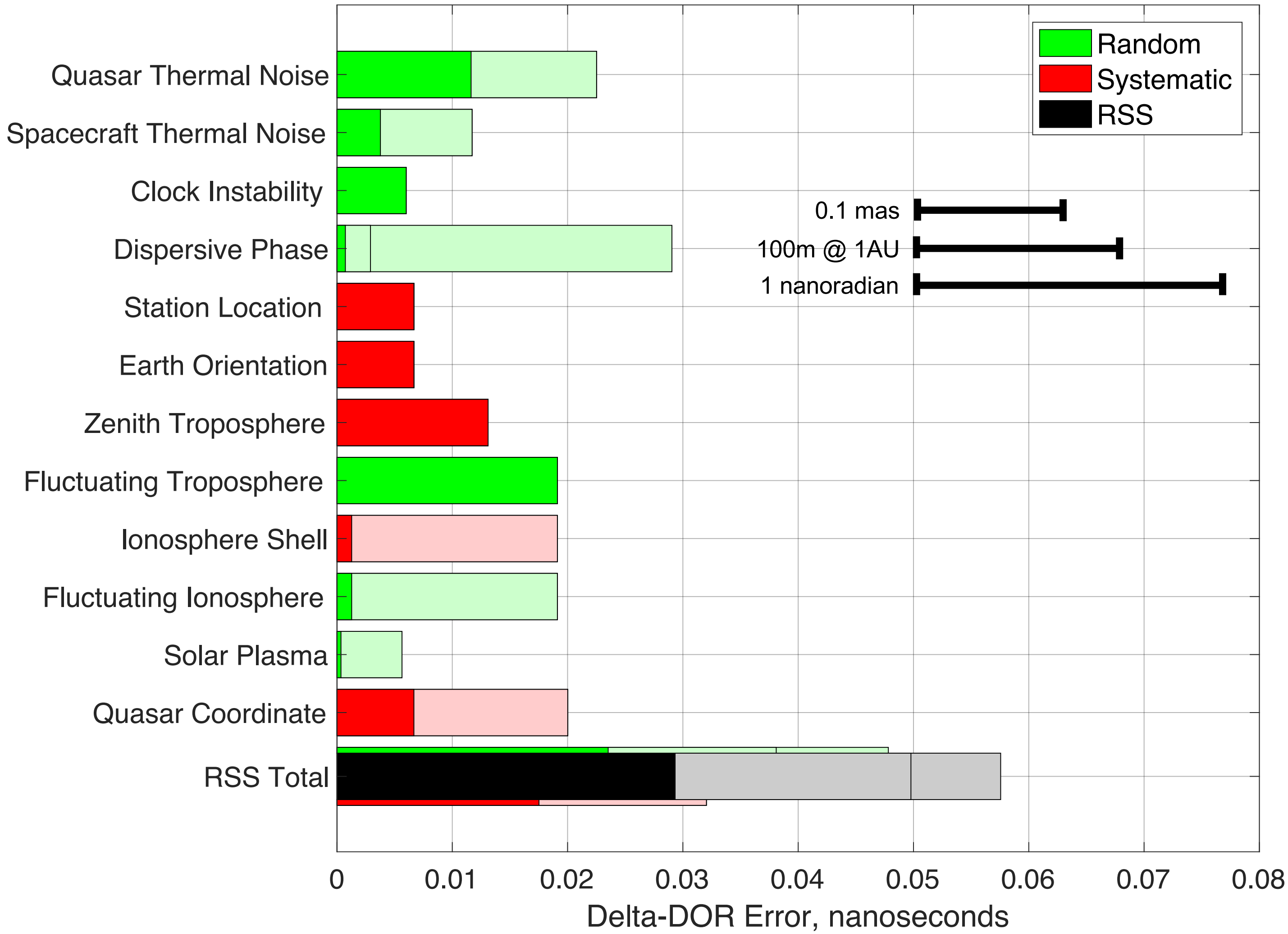
X-Band w/ PN DOR Error Budget



Further Improvement: Ka-Band Delta-DOR

- Remaining error sources can be reduced by going to a higher frequency signal, e.g. Ka-Band (32 GHz)
- Advantages of Ka-Band
  - 4x Wider spanned bandwidth from wider spectrum allocation
  - 4x Higher sampling rates due to increased DOR tone spacing
  - 3x Less quasar coordinate error since quasars generally have smaller cores and less structure at higher frequencies.
  - 15x Less charged particle errors at higher frequency
    - Ionospheric effects and solar plasma effects are greatly reduced
- Disadvantages of Ka-Band
  - 2.5x Less flux from Quasars
  - 2x Increased antenna system temperature

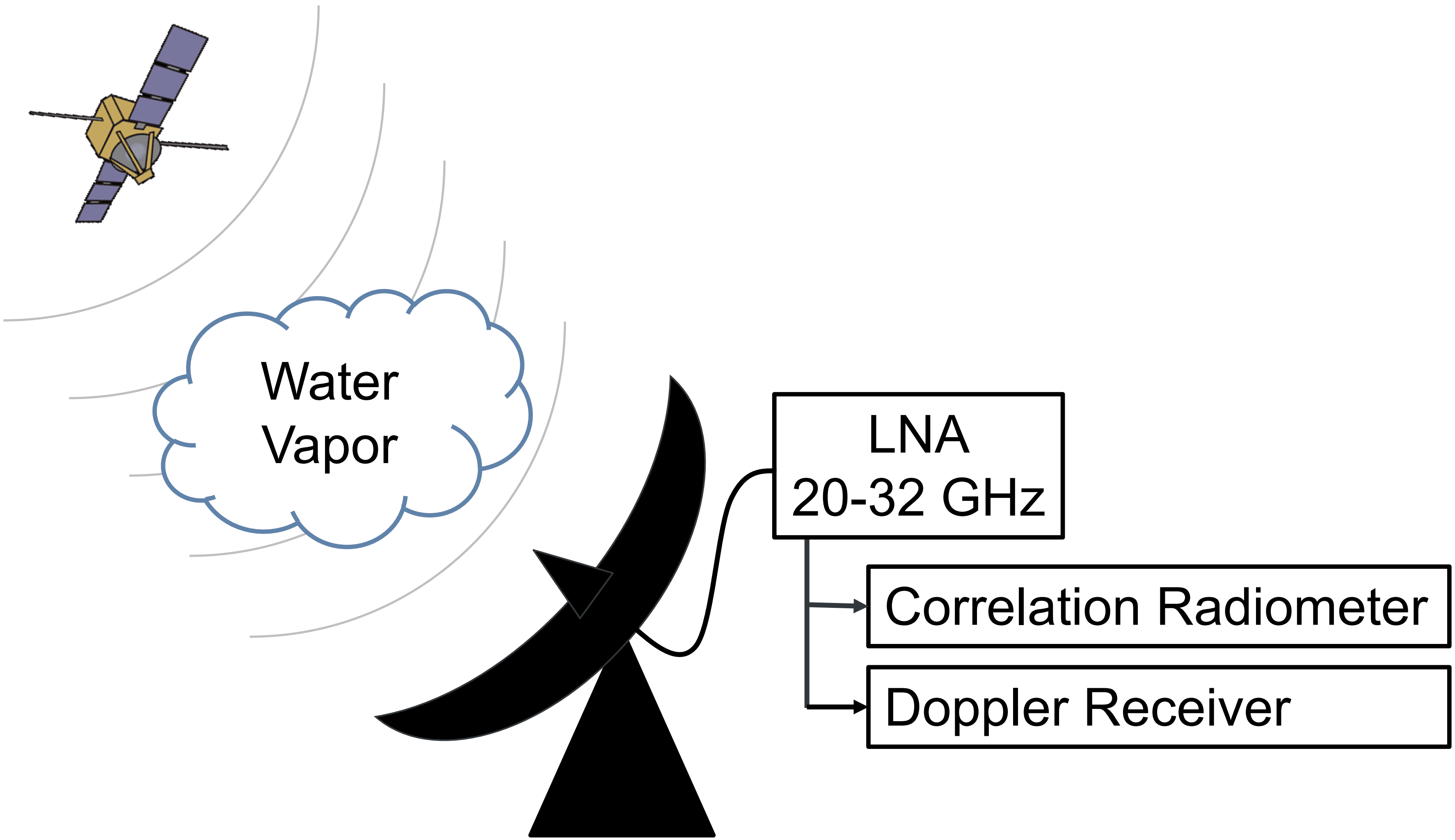
Ka-Band w/ PN DOR Error Budget



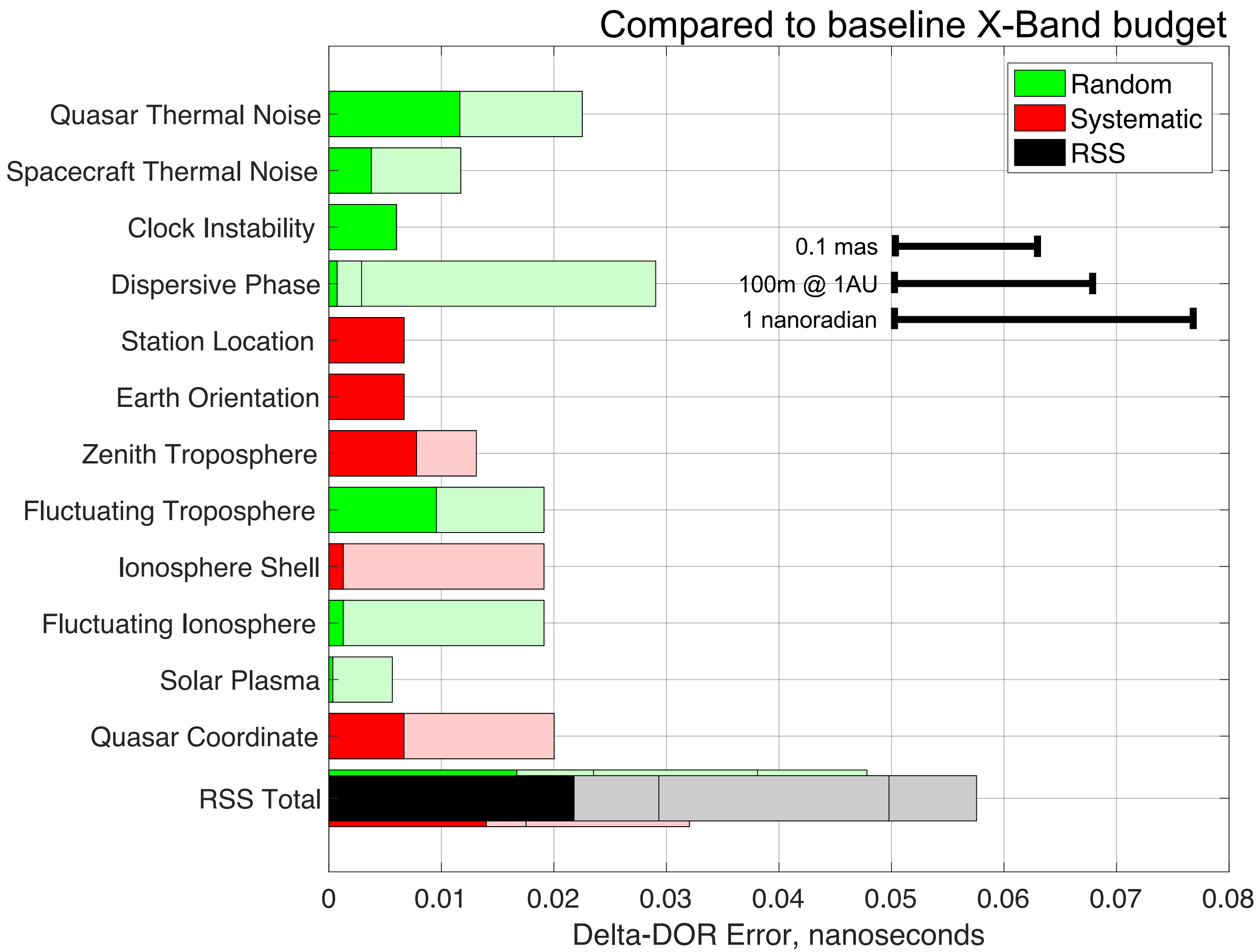
Future Work: Better Troposphere Calibration

- With troposphere remaining as leading error source, developmental technology can reduce troposphere error.
- JPL is developing the In-line Water Vapor Radiometer (WVR) which measures water vapor along the same radio antenna path as the spacecraft signal.
  - Driver is improved Doppler, but will benefit Delta-DOR also
  - Increased performance over short time scales (30-100 seconds)
  - Increased sensitivity over previous designs
- The In-line WVR can be used to calibrate tropospheric errors in Delta-DOR measurements
  - Error reduction by a factor of 2 is expected

In-Line Water Vapor Radiometer Illustration



Ka-Band w/ PN & In-Line-WVR Error Budget



Summary

- Limiting terms within current DDOR error budget include: dispersive phase, ionosphere effects, troposphere effects, and coordinate uncertainty.
- Current technology development efforts aim to reduce leading error sources over next few years.
  - Ka-band (supported now): 15x less ionosphere error, 3x less quasar coordinate uncertainty
  - PN DOR (operational late 2019): 10x less dispersive phase
  - In-line WVR (prototype late 2020): 2x less troposphere error
- With improvements, DDOR one-sigma error budget improves from 2 nanoradian to 0.75 nanoradian.
  - Increased accuracy for Mars landing from 300m to 115m

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